OPTICAL FIBER WITH LOW TAPER INDUCED LOSS

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[0001]   The present invention relates generally to tapered optical fibers and is particularly applicable to optical fibers for use in optical couplers that have low values of nonadiabatic-taper-induced loss.

TECHNICAL BACKGROUND

[0002]   Tapered or heat-treated optical fibers are utilized in fiber pigtails, optical couplers, splicing, connectors and other optical components. As the preformance requirements for the optical components become ever more stringent, the need to eliminate excess loss becomes more critical. One contributor to excess loss is non-adiabatic taper-induced loss.

[0003]   In the tapered regions of fibers the fundamental mode is continuously changing shape to accommodate the changing local index profile. If the rate of change in geometry is too great, the fundamental mode can be coupled to the higher order modes. This mechanism is referred to as a non-adiabatic modal coupling.

[0004]   When the optical fiber is heated, the dopant materials diffuse, changing the local refractive index profile. This occurs, for example, for example, during the splicing process, or during the manufacture of optical coupler devices.   If the rate of change of refractive index (along the length of the fiber) is relatively large, the fundamental mode can be coupled to the higher order modes, resulting in a nonadiabatic index coupling.

[0005]   The relative refractive index ($\Delta\%$) profile (idealized) of a typical telecommunication fiber is illustrated schematically in Fig. 1. Figure 2 illustrates schematically a fiber profile with a depressed index of refraction in the region between the fiber core and the cladding. When tapered, these types of optical fibers exhibit a relatively large amount of non-adiabatic taper-induced loss. Therefore, optical components that include these optical fibers also suffer from

non-adiabatic taper-induced loss. For example, an optical coupler can be fabricated by bringing together two optical fibers and then tapering and fusing them together with an appropriate heat source. However, as the fiber core diameter (in the coupling region) decreases, as compared with the core diameter at the end of each fiber, the coupler exhibits larger amounts of non-adiabatic taper induced loss.

[0006]   US patent 5,412,725 discloses a fiber coupler exhibiting a low non-adiabatic–taper induced loss. The fiber in this coupler has a refractive index profile illustrated in Fig. 3. More specifically, the refractive index profile illustrated in Fig. 3 has a refractive index pedestal characterized by an index of refraction that is intermediate the index n_1 of the core and refractive index n_2 of the cladding. However, as disclosed in col. 6, lines 8 of this reference, the optimal refractive values for the pedestal and pedestal radius were derived without considering such factors as mode field diameter and cutoff wavelength. The presence of a pedestal in the refractive index profile of a fiber results in a different mode field diameter than would be exhibited by a fiber without the pedestal.

SUMMARY OF THE INVENTION

[0007]   According to one embodiment of the invention is an optical fiber comprising: (i) a central core having a relative refractive index delta Δ_C; (ii) a multi-pedestal region in contact with and surrounding the core, said multi-pedestal region having an outer radius of less than 25μm and at least two pedestals, each of the pedestals being in contact and adjacent to at least one other pedestal, each of the pedestals having a relative refractive index Δ_{ped} lower than Δ_C, at least one of the pedestals having Δ_{ped} value higher than 0.2%; and (iii) another region in contact and surrounding the multi-pedestal region, the other region having a relative refractive index delta which is lower than that of any pedestal. According to one embodiment, this region is cladding and at least one of the pedestals has Δ_{ped} value lower than 0.2%.

[0008]   According to another embodiment, the present invention includes an optical fiber comprising: (i) a central core having a relative refractive index delta Δ_C, (ii) a multi-pedestal region surrounding the core, the multi-pedestal region having an outer radius of less than 25μm and at least two pedestals, at least one of the pedestals having relative refractive index delta

value Δ_{ped} higher than 0.2% and a width less than 6 μm; and (iii) a cladding surrounding the multi-pedestal region. The cladding having a relative refractive index delta lower than that of any pedestal.

[0009]   One an advantage of the optical fiber of the present invention is that this fiber, when utilized in optical splicing application, maintains adiabatic modal evolution and, therefore, exhibits low splice loss.   Another advantage of the optical fiber of the present invention is that this fiber can be utilized to manufacture low loss couplers or other tapered-fiber devices.

[0010]   Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0011]   It is to be understood that both the foregoing general description and the following detailed description present illustrative embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]   Figure 1 is a schematic illustration of a relative refractive index profile of a Prior Art optical fiber;

[0013]   Figure 2 is a schematic illustration of a relative refractive index profile of second Prior Art optical fiber;

[0014]   Figure 3 is a schematic illustration of a relative refractive index profile of another optical fiber;

[0015]   Figures 4a and 4b are a schematic illustration of a relative refractive index profile of two illustrative embodiments of the present invention;

[0016] Figure 5 illustrates differences in spacing between the LP_{01} mode and the LP_{02} mode versus the fiber taper ratio, for several fibers with different pedestal region geometry.

[0017] Figure 6 illustrates MFD versus cut-off wavelength for a fiber with a single pedestal and an illustrative fiber of the present invention that includes six pedestals.

[0018] Figure 7 illustrates a relative refractive index profile of an optical fiber that has a pedestal region with two pedestals surrounding the fiber core.

[0019] Figure 8 illustrates a relative refractive index profile of an optical fiber that has a pedestal region containing four pedestals.

[0020] Figure 9 illustrates a relative refractive index profile of an optical fiber that has a pedestal region containing six pedestals.

[0021] Figure 10 illustrates schematically an optical coupler that includes an optical fiber of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0022] Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. An optical fiber of the present invention designated generally throughout by the reference numeral **10**. Two illustrative embodiments of the relative refractive index profiles of the optical fiber **10** are shown schematically in **Figures 4a** and **4b**.

[0023] It is noted that in the relative refractive index profiles depicted in **Figures 1-3 and 4a, 4b** no attempt has been to represent indices and radii to scale and/or exact magnitude.

[0024] As embodied herein and depicted in the fiber profiles of **Figure 4a, 4b**, the optical fiber **10** comprises: (i) a central core **12** having a refractive index n_C, (ii) a multi-pedestal region **14** connected to and surrounding the core **12**, with at least two pedestals **14a** and **14b**; and (iii) a cladding **16** surrounding the multi-pedestal region **14**. It is preferable that the central core radius Rc be about 5 μm or less, and more preferable that Rc≤2.5 μm. It is most preferable that the radius Rc of the central core be between 0.8 μm and 2.5 μm.

[0025] The pedestals are the step-like regions in the relative refractive index profile which indicate progressive refractive index drops within the multi-pedestal region **14** and which are formed by different amounts of index-altering dopant(s). However, although an ideal pedestal has sharp edges, the pedestals may also have rounded or sloped edges as indicated, for example, by the dashed curves of **Figures 4a, 4b**.

[0026] The cladding **16** has an index of refraction n_{Cl} which is either lower than the index of refraction of any of the pedestals, or is preceded by a moat **15** (located between the cladding **16** and the-pedestal region **14**) with the index of refraction n_M lower than the index of refraction of any of the pedestals. The multi-pedestal region **14** has an outer radius R of less than 25μm and preferably less than 20 μm. At least one of the pedestals (**14a**) has Δ_{ped} value higher than 0.2%. Preferably, another one of the pedestals (**14b**) has a Δ_{ped} value lower than 0.2%. The relative refractive index Δ_{ped} of a pedestal is defined as $(n_i^2-n^2)/2n^2$, where n_i is the refractive index of the specific pedestal **14i** and n is the refractive index of the region that is in contact and surrounding the multi-pedestal region **14**. That is, n is ether the refractive index of the cladding **16** or the moat **15**. For example, Δ_{ped} of the third pedestal **14c** equals to $(n_i^2-n_{Cl}^2)/2n_i^2$, where n_i is a refractive index of the pedestal **14c** and n_{Cl} is the refractive index of cladding **16**, shown in **Figure 4a**. Typically, the cladding **16** is made of pure silica. However, it may include index altering dopants.

[0027] It is preferable that the multiple-pedestal region **14** of the optical fiber **10** includes six or fewer pedestals **14i** with Δ_{ped} values higher than 0.2% and the width of each of these pedestals is 6 μm or less. It is even more preferable that the width of each of the pedestals are less 5μm. It is most preferable that the width Wi of each of the pedestals be in the range of 0.2 μm to 4 μm. The width of the pedestals may be determined by the step function approximation to the curved lines. For example, the widths of the pedestals may be determined by inflection points on the plot of the relative refractive index profile. For example, the radius of the core **12** may be measured as the horizontal distance from the vertical axis to the first point of inflection (not accounting for the centerline dip). The radius of the first pedestal **14a** may be determined by the third point of inflection and the width W_a of this pedestal may be measured by the horizontal distance between the first and the third point of inflection. The radius of the third pedestal may

be determined by the third point of inflection and the width W_b of the second pedestal **14b** would then correspond to the distance between the third and the fifth line of inflection. That is, if the relative refractive index profile is similar to that shown by the dashed lines of **Figures 4a** and **4b**, the widths of the pedestals may be determined by the distances between the odd inflection points.

[0028] It is most preferable that the total width of these pedestals with Δ_{ped} values higher than 0.2% is less than 15 μm. It is also preferable that at least one of these pedestals has Δ_{ped} values higher than 0.3% and lower than 0.9%,; more preferably higher than 0.3% and lower than 0.7%.

[0029] The multiple pedestal region **14** modifies the spacing of the propagation constant of the guided mode (also referred to as the fundamental mode) and that of the higher mode(s) (such as LP_{02}, LP_{11}, for example) of the optical fiber **10**. The propagation constant of the guided mode is approximated by the LP_{01} scalar mode. The propagation constant of the higher mode is approximated by the LP_{02} scalar mode. Applicant believes that if coupling from the guided mode LP_{01} to the higher LP_{02} mode is minimized, then coupling from the LP_{01} to the other higher modes will also be minimized.

[0030] A single mode optical fiber will support low-loss propagation of the guided mode LP_{01} and will strip off light propagating in the higher order modes. Thus, coupling of signal light from the guided mode into a higher order mode is undesirable, because this signal light will be lost. However, when the spacing between LP_{01} and LP_{02} modes is small, light tends to couple between the guided and the higher order mode(s).

[0031] Increasing this spacing between the guided mode and the higher order modes (LP_{01}-LP_{02}, at the desired wavelength λ), by addition of the multi-pedestal region **14**, reduces the coupling between the guided mode and the higher order mode(s). As stated above, optical fiber **10** is a single mode fiber and reducing the coupling between the guided mode (LP01) and the higher order mode(s) reduces excess loss and improves fiber efficiency.

[0032] Therefore, increasing the spacing between the LP_{01} and LP_{02} modes in the optical fiber **10** will reduce excess loss for the optical fibers with the same taper geometry. Alternatively, greater spacing between the modes will allow the same loss with steeper tapers, enabling fabrication of more compact (i.e. shorter) devices. It is preferable that the spacing between these

two modes (LP_{01} - LP_{02}), at λ=1550nm be larger than 0.0019 μm^{-1}, which is achieved by the presence of the multi-pedestal region **14**. In the disclosed illustrative embodiments this spacing is between 0.0019 μm^{-1} and 0.003 μm^{-1}. This spacing resulted in non-adiabatic taper induced loss of less than 0.1dB when the fiber taper ratio was in the range of 1.5 and 3. In some embodiments the non-adiabatic taper induced loss was below 0.06 and 0.05 dB.

[0033] Applicant discovered, that unless specifically controlled, introduction of a multiple pedestal region into a fiber changes fiber's MFD and its cut-off wavelength λc, often changing fiber from a single mode to a multi-mode fiber and resulting in loss of MFD match with other fibers for packaging and pigtailing and, in addition, increases fiber's bend loss sensitivity. More specifically, as the MFD value (at the specified wavelength, for example 1550nm) of the optical fiber increases, the bend loss of the optical fiber goes up. Thus, the height and the width of the pedestals should be varied to keep the fallowing two variables substantially constant: (i) the MFD diameter (at the specified wavelength), and (ii) the cut-off wavelength λc.

[0034] More specifically, to design a multiple-pedestal fiber **10**, applicant used, as a starting point, relative refractive index profile of a typical Si /Ge doped fiber without the pedestal region. The amount of germanium in the core region was 18wt%, resulting in $\Delta\%$ =1%. The fiber's cladding was pure Si cladding. Then the first pedestal (at index delta about $\Delta\%$ =0.75 ± 0.15) was added next to the core region, which changed values for both MFD and λc. The width of the pedestal was then scaled down to bring λc to below 980 nm (preferably to 965 nm ± 10 nm). Then the applicant scaled (either up or down), by about 10% increments both the core and the pedestal diameter to attain the target MFD diameter (7μm, at λ=1550nm). This step was repeated, if necessary, with a different increment amount, until the desired MFD and λc were attained. Subsequently, applicant added the next pedestal which again changed values for both MFD and λc. The difference in index delta between the first and the second pedestal was chosen to be at about 0.1% or larger. The width of the next pedestal was then scaled down to bring λc to its target value (preferably to 965nm ± 10 nm). Then the width of both the core and the multi-pedestal region was scaled (either up or down), by about 10% increments to attain the target MFD diameter. The applicant added other pedestals to the pedestal region and preformed the above described scaling steps with the addition of each pedestal. The difference in index delta

between the different pedestals is variable, depending on the number of pedestals in the multi-pedestal region **14.** It is preferable that the difference in index delta between the different pedestals be about 0.05% or larger.

[0035] In the disclosed embodiments of the optical fiber **10** the height and the width of the pedestals was controlled by choosing the proper amount of the index raising dopant. Although in the disclosed embodiment the index raising dopant is Ge, other index raising dopants may also be utilized. More specifically, a standard silica based all core cane(Si/18%wt Ge), may be overclad with Silica/Germania during laydown, for example by an outside vapor deposition OVD processing technique. OVD processing is well known to those of ordinary skill in the art of optical fiber manufacturing, and, therefore, will not be discussed herein. Alternatively, dopants such as boron or fluorine may be utilized to depress the index of the pedestals relatively to one another.

[0036] It is preferable, in order to minimize bend losses, that the fiber's MFD be below 8 μm (at λ=1550 nm). On the other hand, as the MFD decreases, the cut-off wavelength starts to increase and increases rapidly when the fiber MFD is below 6.2 μm (at λ=1550 nm). In the followings illustrative embodiments the optical fiber **10** has mode field diameter MFD between 6 μm and 8 μm (at λ=1550 nm) and a cut-off wavelength λc= 980 μm or less (measured at 2m fiber cut-off). It is preferable that MFD values be in the range of 6.2 μm and 7.7 μm (at λ=1550 nm), and most preferable that MFD values be in the range of between 6.5 μm and 7.5 μm (at λ=1550 nm).

[0037] **Fig. 5** depicts the differences in spacing between the LP_{01} mode and the LP_{02} mode versus the fiber taper ratio for several fibers with different pedestal region geometry. The core size and the core and the cladding compositions of these fibers were identical and the geometry of the pedestals were modified to keep (i) MFD below 8 μm at a wavelength of 1550nm and approximately constant; and (ii) the cutoff wavelength at or below 980nm. In the disclosed embodiments MFD values were targeted to be MFD=7 μm ±0.25 μm (at a wavelength of 1550nm), and the cut off wavelength was targeted to be λc=965nm, ±10nm.

[0038] The excess loss value L is inversely proportional to delta β, or (LP_{01}-LP_{02}). Thus, **Fig. 5** is a graph of inverse Loss μm^{-1} versus fiber taper ratio. It illustrates that the highest loss

(minimum delta β) occurs for taper ratios between 1.4 and 2.6, with the majority of fibers having highest loss when the taper ratio is between 1.6 and 2.4. The taper ratio is the ratio between fiber diameter at non-tapered region and fiber diameter at the narrowest (tapered) region. That is, it is the ratio of initial fiber core diameter to the final fiber core diameter, after the fiber has been tapered.

[0039] **Figure 5** illustrates that a fiber with no pedestal region suffers from most loss (bottom-most curve). The next four curves correspond to the optical fibers with a single pedestal. **Figure 5** shows that fibers with a single pedestal in the pedestal region preforms better than the fiber with no pedestals. The four curves correspond to optical fibers with progressively higher pedestals. The heights of the single pedestals range from 0.016%, to 0.04%. The best results (least loss) was achieved with the higher pedestal (delta of 0.04%). However, we obtain no loss improvement when the height of the single pedestal was increased above this amount.

[0040] The next three curves (from the bottom) of **Figure 5** correspond to the fibers with a two pedestal, four pedestal and six pedestal regions. As stated above the dimensions of the pedestals were chosen to maintain MFD and the cut-off wavelength λc. **Figure 5** illustrates that propagation constant difference progressively increased (i.e., taper- induced loss progressively decreased) as the number of pedestals increased from 1 to 6. However, as the number of pedestals increases, the difficulty in making the optical fiber also increases. This is illustrated in **Figure 6**.

[0041] More specifically, **Figure 6** illustrates MFD versus cut-off wavelength for a fiber with a single pedestal and a fiber with six pedestals. The curve corresponding to the six-pedestal fiber design is much steeper than the curve corresponding to the single pedestal fiber design. This signifies an increased sensitivity of cut-off wavelength to small changes in fiber's core diameter. Thus, in order to decrease the sensitivity of the cut-off wavelength to small changes in fiber core diameter (and, as result, increasing manufacturing yields), it is preferable that optical fiber **10** has two to four pedestals.

EXAMPLES

[0042] The invention will be further clarified by the following examples of the optical fibers containing 2, 4 and 6 pedestals in the pedestal region **14**. Although in these examples the core-

to-cladding delta is 1%, the relative refractive index difference between the core and the cladding may be larger or smaller.

EXAMPLE 1

[0043] **Figure 7** illustrates a relative refractive index profile of an optical fiber **10** that has a central core region **14** with two pedestals **14a, 14b** surrounding the central core **12**. The fiber's central core radius Rc is about 1.25 μm. Pedestal **14a** is characterized by the relative index delta Δ_1 of 0.6% and is about 0.8 μm wide. The outer radius R_1 of the first pedestal **14a** is about 2 μm. Pedestal **14b** is characterized by the index delta Δ_2 of about 0.04% and is about 1.6 μm wide. The outer radius R_2 of the second pedestal **14a** is about 3.8 μm. The total width of the pedestal region **14** is about 2.5 μm and its outer radius is about 3.8 μm ($R=R_2$). The core of the fiber contains about 18 wt% Ge, while the pedestal regions **14a, 14b** contain about 11 wt% and 0.7% wt Ge, respectively.

EXAMPLE 2

[0044] **Figure 8** illustrates a relative refractive index profile of an optical fiber **10** that has a central core region **14** with four pedestals **14a, 14 b, 14c and 14d** surrounding the central core **12**. The fiber's central core radius Rc is about 1 μm. Pedestal **14a** is characterized by the index delta Δ_1 of about 0.9% and is about 0.5 μm wide. The outer radius R_1 of the first pedestal **14a** is about 1.5 μm. Pedestal **14b** is characterized by the index delta Δ_2 of 0.64% and is about 0.2 μm wide. The outer radius R_2 of the second pedestal **14b** is about 1.7 μm. Pedestal **14c** is characterized by the index delta Δ_3 of about 0.4% and is about 0.3 μm wide. The outer radius R_3 of the third pedestal **14c** is about 2 μm. Pedestal **14d** is characterized by the index delta Δ_4 of about 0.08% and is about 1.2 μm wide. The outer radius R_4 of the fourth pedestal **14d** is about 3.2 μm. Thus, the total width of the pedestal region **14** is about 2.5 μm and it outer radius is about 3.2 μm. The core of the fiber contains about 18wt% Ge, while the pedestal regions **14a, 14b, 14c and 14d** contain about 16 wt%, 11.5 wt %, 7wt % and 1.5% wt of Ge, respectively.

EXAMPLE 3

[0045] **Figure 9** illustrates a relative refractive index profile of an optical fiber **10** that has a core region **14** with six pedestals **14a, 14b, 14c, 14d, 14e and 14f** surrounding the core **12**. The fiber's central core radius Rc is about 0.9 μm. Pedestal **14a** is characterized by the index delta

Δ_1 of about 0.9% and is about 0.3μm wide. Pedestal **14b** is characterized by the index delta Δ_2 of 0.8% and is about 0.3μm wide. Pedestal **14c** is characterized by the index delta Δ_3 of about 0.6% and is 0.4μm wide. Pedestal **14d** is characterized by the index delta Δ_4 of 0.4% and is 0.3μm wide. Pedestal **14e** is characterized by the index delta Δ_5 of 0.09% and is about 0.7μm wide. Pedestal **14f** is characterized by the index delta Δ_6 of 0.02% and is 2 μm wide. The total width of the pedestal region **14** is 4 μm and it outer radius is about 5μm. The central core of the fiber contains about 18% Ge, while the pedestals **14a-14e** contain progressively lower amounts of Ge. Pedestal **14f** contains about 2wt% chlorine Cl, and no Ge.

[0046] The optical fiber **10** can be manufactured by the process similar to the one described, for example, in US Patent 5,295, 211. More specifically, Ge and SiO_2 are supplied (in vapor form) and deposited on a mandrel. After the central core region is deposited, Ge gas flows are reduced (to provide lower level of Ge) for the first pedestal, and further reduced in successive pedestals. The mandrel is removed and the resultant tubular (core/pedestal) preform is gradually inserted into a consolidation furnace muffle, at the temperature of about 1500°C (1200°C - 1700°C) for high silica content glass.

[0047] Chlorine gas (which is normally present during the preform consolidation step to achieve drying) may be supplied into the preform aperture as a drying gas during consolidation. A helium flushing gas is simultaneously flowed through the muffle.

[0048] The resultant tubular article is heated and drawn in a standard draw furnace while a vacuum is applied to the aperture to form a "core/pedestal rod" in which the aperture has been closed. A suitable length of rod is supported in a lathe where particles of silica are deposited thereon. The resultant final porous preform is inserted into a consolidation furnace where it consolidated while a mixture of chlorine and helium is flowed upwardly through the furnace. The resultant glass preform is overclad with, for example, ure silica to produce a fiber preform, which is then, drawn to form a single mode optical fiber.

[0049] The amount of Ge applied to the core/pedestal preform determines the radius of the pedestal region **14** and the heights (Δ_{pd}) of the pedestals **14i**. In absence of other index effecting dopants addition of 18wt% of Ge to pure silica corresponds to the relative refractive index delta of about 1%, and the effect of adding Ge dopant is linear. If chlorine has been added, the amount

of chlorine to which the porous portion of the preform is subjected to during second drying/consolidation step will also effect (increase) the value of Δ_{ped}.

[0050] The resultant optical fiber 10 may be tapered to produce a low-loss optical coupler 50. Such an optical coupler is illustrated schematically in **Fig. 10**. Coupler 50 includes two single mode optical fibers **10a, 10b**, which can be situated within the overclad tube **52**. At least one and preferably both of these fibers include the multi-pedestal region 14 situated between the core 12 and another region (cladding 16 or moat 15). The original diameter of the tube is d_1. The central portion of the stretched mid-region constitutes neckdown region N of diameter d_2 where the fiber cores are sufficiently closely spaced for a sufficiently long distance Z to effect the desired coupling therebetween. Region N is illustrated as having a constant diameter even though a slight taper exists therein, whereby the longitudinal center of section N exhibits minimum diameter. Fiber taper ratio is approximately the draw ratio d_1/d_2. Tapered regions T connect the neckdown region with the unstretched end regions of the overclad tube **52**. Alternatively, the two fibers may be placed in proximity with one another, heated and tapered, without the overclad tube **52**. The coupler fibers **10a, 10b** would have taper ratio between 1.5 and 4.

[0051] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.